

PQ Technical Application Guide

Power Quality Questions and Solutions



1. Introduction

This paper begins with the assumption that the reader has some basic knowledge of power system harmonics in Power Quality. As a simple refresher – the general acceptable explanation is that harmonic currents flow or are “sourced” from loads and create voltage distortion (or harmonic voltages) as they pass through upstream power system impedance components such as cables, transformers, and generators. In general, the further away from the source of harmonic currents (i.e. the loads), the less voltage distortion you will see. Certainly exceptions exist and harmonic voltages may be “produced” by some equipment (some generators, for example) but the general discussion of this paper deals with standard considerations when dealing with typical harmonic producing loads in commercial and industrial power systems.

Problems associated with harmonic distortion are well understood for many power system applications. However, finding the right solution is challenging. There are at least ten different technologies to choose from, each with specific technical and economic advantages. This presentation will provide recommendations for reducing harmonic distortion, improving system capacity and improving system reliability while evaluating economic considerations. Special considerations for applying capacitors on a power system with harmonics will be discussed. Finally, opportunities for improving energy efficiency using harmonic technologies will be explained.

2. PQ Solutions for Power Customers

Power quality has become increasingly important for industrial and commercial electric power customers, particularly as manufacturing and control processes more

heavily rely on equipment sensitive to power system interruptions and disturbances. Increased automation of manufacturing and other industrial processes and expanded use of energy-efficient power electronic technologies and microprocessor-controls are forcing customers to pay more attention to power quality issues.

Electrical power cannot be effectively stockpiled and inspected for quality before it is delivered. As a result, power quality problems usually go undetected until after a disturbance occurs and processes are interrupted, equipment damaged, and product spoiled. Unless the source of the disturbance is identified, and its cause diagnosed and repaired, the costs can be huge.

Power quality issues can originate with a power provider or within your facility. Poor quality power can have hundreds of sources. Voltage sags can result from utility transmission line faults, or at your end, because of motor start ups, defective wiring, and short circuits, which reduce voltage until a protective device kicks in. Transients may occur due to utility capacitor bank switching, or from incorrect grounding at your site. Harmonics can also be generated within your facility, from non-linear loads such as variable speed motor drives, arc furnaces, and fluorescent ballast.

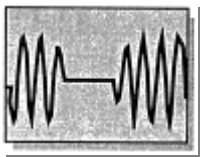
Gentec inc provides extensive power quality evaluation and solutions for industrial and other commercial facilities. We can provide solutions to existing power quality problems, as well as recommendations to ensure optimal power quality for facilities under construction or renovation. These solutions, including fixes, automatic, dynamic or active assessments, can be used to effectively solve and even prevent power quality problems.

3.0 Common Power Quality Problems

Through our work with all sorts of facilities, we've identified three different significant types of power quality problems:

3.1 Voltage Momentary Interruptions.

Increased sensitivity of power electronic equipment, coupled with the high likelihood of voltage sags and interruptions, has resulted in these being the most visible power quality events. Adjustable speed drives, computers, office equipment, programmable controllers, and induction heating furnaces can be extremely sensitive to these events. Typically, sags occur when there are temporary faults on the utility power system, resulting in a reduction in the voltage level.



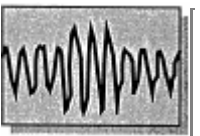
- **Voltage interruption**
Voltage fail.

Voltage sags are more numerous than momentary interruptions because to experience a momentary or permanent interruption, you must be located on the faulty line section. Equipment sensitivity to these events is important because nuisance tripping of sensitive industrial loads can cause equipment downtime, reduce productivity, and hurt your bottom line.

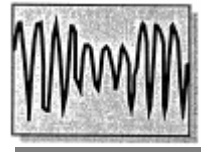
3.2 Sags and Swells

Sags and swells represent a short duration increase or decrease in RMS voltage or current ranging between 10% and 90% of the nominal. The duration can range from ½ a cycle to 2 sec. Common sources of sags and swells include:

- Electrical system faults
- Start-up of heavy loads
- Lightning



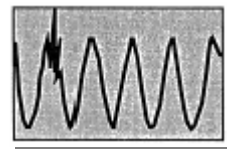
- **Voltage Swell or over Voltage**
RMS voltage reduction = 15 mSec to 2 sec



- **Voltage Sag or under Voltage**
RMS voltage reduction = 15 mSec to 2 sec

3.3 Transients.

Transients consist of sudden frequency and amplitude changes in voltage and/or current waveforms. There are two main types of transients, impulsive and oscillatory. Transients cause electronic component failures and shutdown of variable speed drives (VSDs), and typically last a few hundred microseconds. For example, a 2000V impulsive transient can rise from zero to its peak value of 2000V in 1.2 µsec, then decays to half its peak value in 50 µsec.



- **Transient**
Electric signal present on the voltage wave form

AC and dc drives, along with other electronic loads, can be very sensitive to transient voltages. The tolerance levels of these devices are often less than other loads such as standard motors. Metal oxide varistors used in these drives to provide transient voltage protection have low energy tolerance capabilities. When the varistors fail during a transient, a short circuit occurs, causing the drive to trip. A major concern for transient voltages occurs with possible magnification of utility capacitor switching transients at low-voltage capacitor locations on customer power systems.

Common sources of transients include:

- Lightning
- Capacitor bank switching
- Large variable speed drives
- Electrostatic discharges
- Faulty wiring

- Battery chargers
- Uninterruptible power supplies

3.4 Flicker

Flicker is a term used to describe a random or continuous voltage fluctuations no more than 10% lower or higher than the normal voltage waveform. These fluctuations cause perceptible lamp (lighting) flicker, even at magnitudes as low as 0.5% and frequencies of 6 Hz to 8 Hz. Common sources of flicker include:

- The repeated connection and disconnection of rapidly fluctuating loads such as arc furnaces
- Electric welders

3.5 Noise

Electrical noise consists of unwanted high frequency signals (lower than 200 kHz) that are superimposed on voltage or current waveforms, resulting in a distortion of the power signal. Noise causes undesirable effects in electronic equipment including PCs and programmable controllers. Common sources of noise include:

- Electrical motors and motor control devices
- Arcing equipment
- Solid-state rectifiers, and switching power supplies



- **Noises**
Electric signal present on the voltage wave form

3.6 Harmonics.

Harmonics represent a distortion of the current sine wave, frequently caused by non-linear loads that generate a frequency other than the standard 60 or 50 cycles per second. Harmonic currents, and the voltage distortion they create, can reduce equipment operating reliability and service life. Common sources of harmonics include:

- Variable speed drives
- Switching power supplies such as those in computers

Variable speed AC and DC drives, along with switch-mode power supplies, cause harmonic currents due to their nonlinear characteristics. These harmonic currents can combine with system frequency response characteristics to cause harmonic voltage distortion. This distortion can cause control malfunction, capacitor failures, motor and transformer overheating, and increased system losses. These problems are compounded by the use of capacitor banks, which can cause resonance conditions magnifying the harmonic distortion levels. These banks are normally installed for power factor correction purposes, as well as to free up transformer capacity. IEEE's 519 standard specifies strict current distortion limits that can prove difficult to comply with.

When we do facility power system studies, we look at a range of specific issues

- Harmonic Analysis
- Utility capacitor switching activities
- Voltage variation analysis
- Power factor correction

Figure 3.6a illustrates a sample power system with several harmonic sources and solutions that will be discussed in this paper.

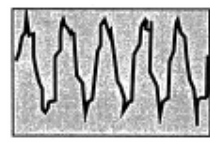


fig. 3.6a

- **Harmonics : (Volts or Current)**
This is the continuous and permanent wave form which the multiples frequencies is base on the fundamental (60Hz)

Any harmonic producing load should operate normally when applied as a single load on a system without other harmonic sources. Combinations of other factors including the number of non-linear loads (more importantly, their combined kVA rating), the existence of capacitors and other factors affect how harmonic-producing loads interact with the system, including other linear loads. A linear load, like a motor, will draw a non-linear current (i.e. containing harmonics) if the voltage is distorted. This is often a confusing issue but the motor is simply drawing a current that is proportional,

at each frequency, to its source voltage based upon the motor impedance.

Only a motor fed by a purely 60 (or 50) Hz source will draw a current without harmonic content.

The application of power factor correction capacitors requires special consideration when they are applied on a system where harmonic loads exist or may exist in the future. Capacitors can make a moderate harmonic problem significant and can lead to excessive damage and/or nuisance operation of equipment.

The following symptoms are examples of **equipment failure and misoperation** associated with harmonics on a power system.

- Voltage notching
- Erratic electronic equipment operation
- Computer and/or PLC lockups
- Overheating (motors, cables, transformers, neutrals)
- Motor vibrations
- Audible noise in transformers and rotating machines
- Nuisance circuit breaker operation
- Voltage regulator malfunctioning
- Generator regulator malfunctioning
- Timing or digital clock errors
- Electrical fires

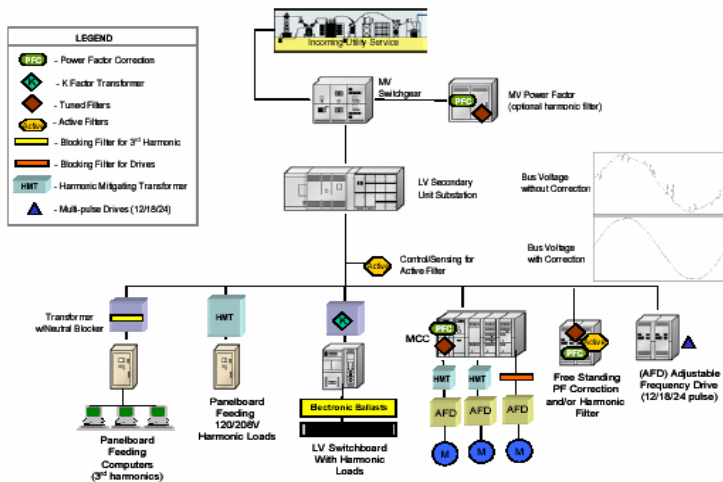


Figure 1 – Sample of Harmonic Sources and Solutions

The following are **economic considerations** that should be evaluated with regard to harmonics.

- Losses/inefficiency (motors)
- kW losses in cables and transformers
- Low total power factor
- Generator sizing considerations
- UPS sizing consideration
- Capacity concerns (transformers, cables)
- Utility imposed penalties

4.0 Harmonics symptoms

How do you know you have a problem? The only way to know is to identify symptoms of harmonics. Very often, if you recognize specific symptoms of harmonics, the problem has already created issues on your power system. The trick is to recognize “potential” symptoms and identify potential harmonic issues before they occur or to implement correction into the system design. Sometimes modeling and simple calculations will help identify the issues before they become a problem.

Symptoms of harmonic problems can be divided into four major areas: Equipment failure and misoperation, economic considerations, application of power factor correction capacitors and other issues.

Applying power factor correction capacitors requires special considerations with regard to harmonics.

- Capacitor failures
- Fuse or breaker (feeding capacitors) nuisance tripping
- Calculated or measured harmonic resonance conditions (series or parallel resonance)

Each one of these symptoms or issues could be discussed in it’s own technical paper but suffice it to say that the magnitude of the “cost” of these symptoms is typically proportional to the complexity and cost of the solution.

4.1 Basics of the harmonics phenomena:

Harmonic currents and voltages are created by non-linear loads connected on the power distribution system. Harmonic distortion is a form of pollution in the electric plant that can cause problems if the sum of the harmonic currents increases above certain limits.

All power electronic converters used in different types of electronic systems can increase harmonic disturbances by injecting harmonic currents directly into the grid. Figure 4.1a shows how the current harmonics (ih) in the input current (is) of a power electronic converter affect the supply voltage (ut).

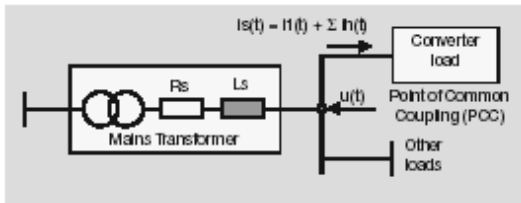


Figure 4.1a Plant with converter load, mains transformer and other loads.

The line current of a 3-phase, 6-pulse rectifier can be calculated from the direct output current by using the following formula.

$$I_1 = \sqrt{\frac{2}{3}} \cdot I_d \quad , \text{where}$$

I_1 = the total RMS current and
 I_d = direct current output from the rectifier. (valid for ideal filtered DC current)

The fundamental current is then

$$I_1 = I_1' \cdot \frac{3}{\pi}$$

In a theoretical case where output current can be estimated as clean DC current, the harmonic current frequencies of a 6-pulse three phase rectifier are n times the fundamental frequency (50 or 60 Hz). The information given below is valid in the case

when the line inductance is insignificant compared to the DC reactor inductance. The line current is then rectangular with 120° blocks. The order numbers n are calculated from the formula below:

$$n = 6k \pm 1, \text{ where } k = 1, 2, 3, \dots$$

The rms values of the harmonic components are:

$$I_n = \frac{I_1}{n}$$

and the harmonic components are as shown in Figure 4.1b.

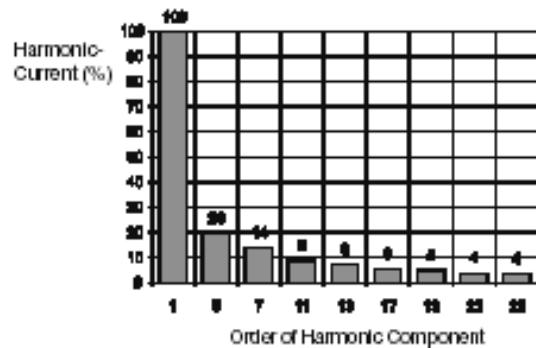


Figure 4.1b The harmonic content in a theoretical rectangular current of a 6-pulse rectifier.

The principle of how the harmonic components are added to the fundamental current is shown in Figure 4.1c, where only the 5th harmonic is shown.

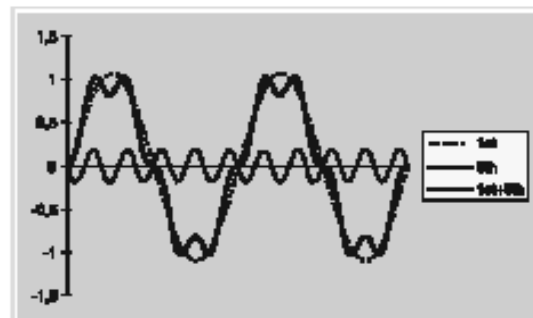


Figure 4.1c The total current as the sum of the fundamental and 5th harmonic.

5.0 Harmonic distortion sources and effects:

Common non-linear loads include motor starters, variable speed drives, computers and other electronic devices, electronic

lighting, welding supplies and uninterrupted power supplies.

The effects of harmonics can be overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics. Electronic displays and lighting may flicker, circuit breakers can trip, computers may fail and metering can give false readings.

If the cause of the above mentioned symptoms is not known, then there is cause to investigate the harmonic distortion of the electricity distribution at the plant. The effects are likely to show up in the customer's plant before they show on the utility system. This Technical Guide has been published to help customers to understand the possible harmonic problems and make sure the harmonic distortion levels are not excessive.

5.1 Evaluating harmonic:

The "Guide for Applying Harmonic Limits on Power Systems" IEE 519 introduces some general rules for evaluating harmonic limits at an industrial facility. The procedure is shown in the flowchart in Figure 5.1a.

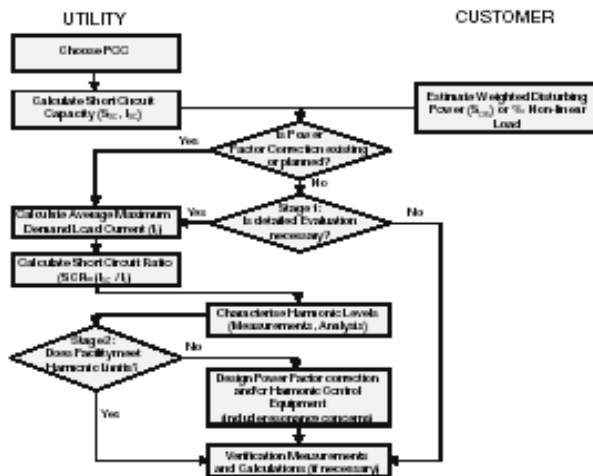


Figure 5.1a Evaluation of harmonic distortion.

IEEE STD 519-1992

IEEE Std 519-1992 is "The IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems". Tables 5.1b and 5.1c define the recommended limits for total harmonic distortion (THD) and individual harmonic

distortion for voltage and current at the point-of-common coupling (PCC) with the utility.

| Voltage Distortion Limits | | |
|---------------------------|-----------------------------------|----------------------------------|
| At PCC | Individual Voltage Distortion (%) | Total Voltage Distortion THD (%) |
| > 69 Kv | 3.0 | 5.0 |
| 69 to 161 Kv | 1.5 | 2.5 |
| > 161 Kv | 1.0 | 1.5 |

Table 5.1b – IEEE Std 519-1992

| Current Distortion Limits General Distribution System (120 V. through 69000 Volts) | | | | | | |
|--|---------------------------------|--------|--------|--------|-------|------|
| Maximum Harmonic Current Distortion in Percent of I _L | | | | | | |
| I _{sc} /I _L | Individual Harmonic Order (odd) | | | | | TDD |
| | <11 | 11to17 | 17to23 | 23to35 | >35 h | |
| < 20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

Table 5.1c – IEEE 519 Current Distortions Limits

5.2 Sample specifications in excess of the IEEE recommendation:

The following is wording from a sample specification. Note: this is not a recommendation but rather a sample of misinterpretation of the IEEE 519 for a drive installation.

The harmonic distortion values resulting from the operation of all or any variable frequency drive-driven motor load combinations operating at full load shall be limited as defined in the latest edition of IEEE Standard 519.

This statement is OK but, by the standard, applies only to the PCC (point-of-common-coupling) with the utility – not as defined here. This brings up the broader discussion of the location of the PCC (see following section on PCC). Interestingly, even with this statement as a header (in the same specification), statements 1, 3 and 4 below contradict the IEEE 519 recommendations.

1. Maximum allowable total harmonic voltage distortion (THD): 3% of fundamental
2. Maximum allowable individual frequency harmonic voltage distortion: 3% of fundamental

3. Maximum allowable individual frequency and total harmonic current demand distortion (TDD): 5% of fundamental
4. The harmonic distortion levels shall be specific to the switchboard bus supplying one unit or a group of variable frequency drives
5. The cost of any and all corrective equipments to limit the harmonic levels to these values shall be the responsibility of the manufacturer.

While this specification will significantly minimize any power system harmonics well below any desirable levels, it is clearly beyond the recommendations put forth by the standard. As it turns out, the specifying engineer will cover any potential problems before they occur but will significantly

Increase the cost of the job. A more practical approach is recommended. That being said, the cost of corrective equipment after the fact is typically higher so the required limitations should be considered and some concessions should be made to both fulfill the IEEE requirements while implementing a practical solution.

5.3 Voltage or current harmonics?

Another statement related to IEEE 519 that often causes significant controversy is the following:

The selected firm is to design and implement remedies that would reduce the total harmonic distortion on the secondary side of the main service transformer to less than 5%.

The question in this case is – voltage or current harmonics? The main concern of the standard is voltage distortion. In some cases where the I_{sc} / I_L is low (i.e. the loading is a high percentage of the system capacity), the current distortion limit is 5% (but merely to minimize the voltage distortion). The IEEE 519 Standard clearly states that harmonic currents should be reduced to minimize voltage distortion. Harmonic currents should also be reduced to minimize loading on the system but even the maximum allowable (20%) distortion will only increase the total root-mean-square (rms) current by approximately 2%.

PCC (Point Common Coupling)

By the Standard, the PCC is where other utility customers can be served and is not necessarily the secondary of the main service transformer and is certainly not a downstream panel board, MCC, feeder or load. Note that sometimes in utility contracts, the PCC can be explicitly defined at locations other than as defined in IEEE 519, such as a metering point. Also, be wary of equipment manufacturer, contractors or engineers insisting that a single load must comply with the IEEE-519 voltage and current recommendations. This was never the intention of the standard.

6.0 Harmonic distortion in Drive:

The harmonic currents cause a distortion of the line voltage. In principle the voltage harmonics can be calculated at any point of the network if the harmonic currents and the corresponding source impedance are known. The circuit diagrams in Figure 6.0. show the network supplying the converter and the other essential parts of the installation.

Circuit diagram for the calculation **example** :

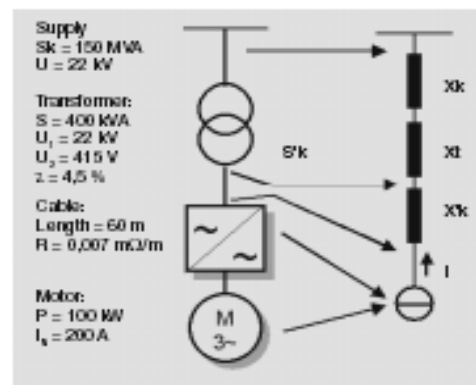


Figure 6.0. Network supplying a frequency converter in the middle and its equivalent diagram on the right. The data for this example is on the left.

6.1 How to reduce harmonics by structural modifications in the AC drive system:

Factors in the AC drive having an effect on harmonics. Harmonics reduction can be done either by structural modifications in the drive system or by using external filtering.

The structural modifications can be to strengthen the supply, to use 12 or more pulse drive, to use a controlled rectifier or to improve the internal filtering in the drive.

Figure 6.1a shows the factors in the AC drive system which have some influence on harmonics. The current harmonics depend on the drive construction and the voltage harmonics are the current harmonics multiplied by the supply impedances.

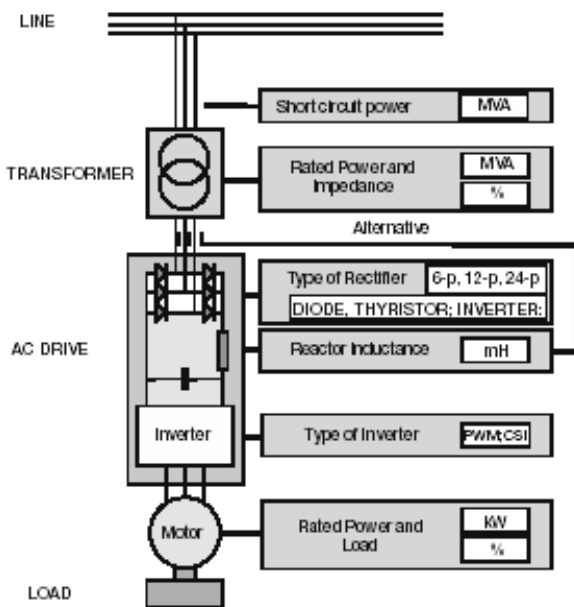


Figure 6.1a Drive system features affecting harmonics.

How to reduce harmonics by structural modifications in the AC drive system.

List of the different factors and their Effects :

| The Cause | The Effect |
|---|-----------------------|
| The larger motor... | + harmonic current |
| Higher motor load | + harmonic current |
| Larger DC / AC line reactor | Less harmonic current |
| Higher number of pulsing rectifier | Less harmonic current |
| Larger transformer | Less harmonic current |
| Lower transformer impedance | Less harmonic current |
| Higher short circuit capacity of supply | Less harmonic current |

7.0 HARMONIC SOLUTIONS

The following are harmonic solutions that are commercially available products or combinations of products for reducing harmonic currents and minimizing harmonic voltage distortion on a power system.

▪ **Drives and Rectifier Solutions**

The following solutions are for drive or three-phase rectifier (large UPSs, for example) applications where a significant amount of harmonic current is generated.

7.1 Using 6-pulse diode rectifier

The connections for different rectifier solutions are shown in Figure 6.2a. The most common rectifier circuit in 3-phase AC drives is a 6-pulse diode bridge. It consists of six uncontrollable rectifiers or diodes and an inductor, which together with a DC-capacitor forms a low-pass filter for smoothing the DC current.

The inductor can be on the DC- or AC-side or it can be left totally out. The 6-pulse rectifier is simple and cheap but it generates a high amount of low order harmonics 5th, 7th, 11th especially with small smoothing inductance.

The current form is shown in Figure 7.1a. If the major part of the load consists of converters with a 6-pulse rectifier, the supply transformer needs to be oversized and meeting the requirements in standards may be difficult. Often some harmonics filtering is needed.

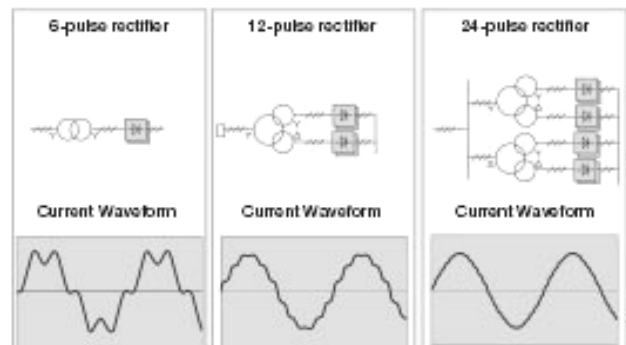


Figure 7.1a Harmonics in line current with different rectifier constructions.

7.2 Using 12-pulse or 24- pulse diode rectifier

The 12-pulse rectifier is formed by connecting two 6-pulse rectifiers in parallel to feed a common DC-bus. The input to the rectifiers is provided with one three-winding transformer. The transformer secondary are in 30° phase shift. The benefit with this arrangement is that in the supply side some of the harmonics are in opposite phase and thus eliminated. In theory the harmonic component with the lowest frequency seen at the primary of the transformer is the 11th.

The major drawbacks are special transformers and a higher cost than with the 6-pulse rectifier.

The principle of the 24-pulse rectifier is also shown in Figure 7.1a. It has two 12-pulse rectifiers in parallel with two three winding transformers having 150° phase shift. The benefit is that practically all low frequency harmonics are eliminated but the drawback is the high cost. In the case of a high power single drive or large multidrive installation a 24-pulse system may be the most economical solution with lowest harmonic distortion.

➤ Advantages

- Reasonable cost, although significantly more than reactors or chokes
- Substantial reduction (up to approx. 85%) in voltage and current harmonics
- Provides increased input protection for VFD and its semiconductors from line transients

➤ Disadvantages

- Impedance matching of phase shifted sources is critical to performance
- Transformers often require separate mounting or larger VFD enclosures
- May not reduce distribution harmonic levels to below IEEE Std 519-1992 guidelines.

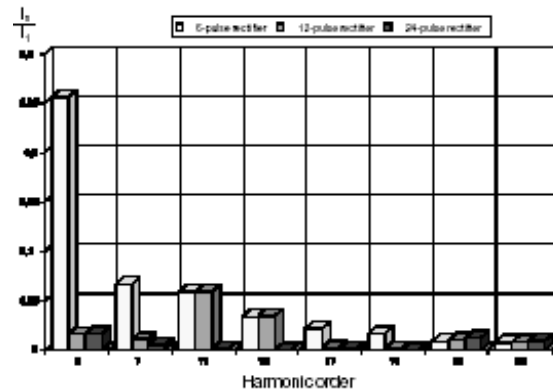


Figure 67.1b Harmonic components with different rectifiers.


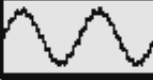

7.3 Using phase controlled thyristor Rectifier:

A phase controlled rectifier is accomplished by replacing the diodes in a 6-pulse rectifier with thyristors. Since a thyristor needs a triggering pulse for transition from nonconducting to conducting state, the phase angle at which the thyristor starts to conduct can be delayed. By delaying the firing angle over 90°, the DC-bus voltage goes negative. This allows regenerative flow of power from the DC-bus back to the power supply.

Standard DC-bus and inverter configurations do not allow polarity change of the DC-voltage and it is more common to connect another thyristor bridge anti-parallel with the first one to allow the current polarity reversal. In this configuration the first bridge conducts in rectifying mode and the other in regenerating mode.

The current waveforms of phase controlled rectifiers are similar to those of the 6-pulse diode rectifier, but since they draw power with an alternating displacement power factor, the total power factor with partial load is quite poor. The poor power factor causes high apparent current and the absolute harmonic currents are higher than those with a diode rectifier.

In addition to these problems, phase-controlled converters cause commutation notches in the utility voltage waveform. The angular position of the notches varies along with the firing angle.

| Supply type | Current TDH (%) | Voltage TDH (%) RSC=20 | Voltage TDH (%) RSC=100 | Current Waveform |
|--------------------|-----------------|---------------------------|----------------------------|---|
| 6-pulse rectifier | 30 | 10 | 2 |  |
| 12-pulse rectifier | 10 | 6 | 1.2 |  |
| IGBT Supply Unit | 4 | 8 | 1.8 |  |

Distortion is in % of RMS values

Figure 7.3 Distortion of different supply unit types. Values may vary case by case.

7.4 Using IGBT bridge

Introducing a rectifier bridge, made of self commutated components, brings several benefits and opportunities compared to phase commutated ones. Like a phase commutated rectifier, this hardware allows both rectification and regeneration, but it makes it possible to control the DC-voltage level and displacement power factor separately regardless of the power flow direction.

The main benefits are:

- Safe function in case of mains supplies disappearance.
- High dynamics of the drive control even in the field weakening range.
- Possibility to generate reactive power.
- Nearly sinusoidal supply current with low harmonic content. Measured results for one drive are shown in Figure 7.4b. When comparing with Figure 7.1a we can see a clear difference. IGBT has very low harmonics at lower frequencies, but somewhat higher at higher frequencies.
- Voltage boosts capability. In case of low supply voltage the DC voltage can be boosted to keep motor voltage higher than supply voltage.

The main drawback is the high cost coming from the IGBT bridge and extra filtering needed.

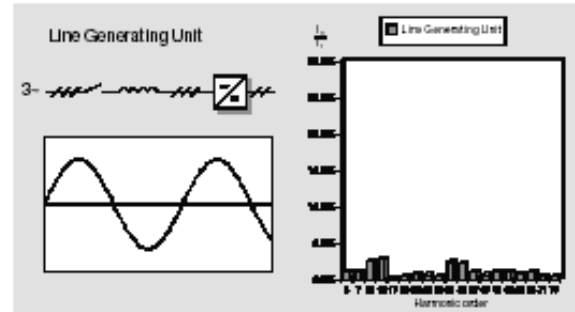


Figure 7.4b Harmonics in line current IGBT line generating unit.

7.5 Line Reactors

A Line Reactor (choke) is a 3-phase series inductance on the line side of a drive. If a line reactor is applied on all VFDs, it is possible to meet IEEE guidelines where up to 15% to 40% of system loads are VFDs, depending on the stiffness of the line and the value of line reactance. Line reactors are available in various values of percent impedance, most typically 1-1.5%, 3%, and 5%.

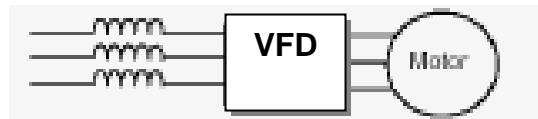


Figure 7.5a – Line Reactor

IEEE 519 shows an example of the benefit of using line reactors in Figure 7.5b. Table 7.5c is a summary of the typical current distortion for a drive with a line reactor of varying sizes.

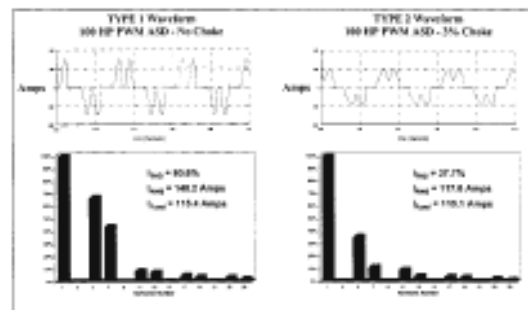


Figure 7.5b - IEEE 519 – Benefit of Line reactor

| Line Reactor | Expected Individual Drive Harmonic Current Distortion |
|--------------|---|
| 1 % | 80 % |
| 3 % | 35 % to 45 % |
| 5 % | 30 % to 35 % |

Table 7.5c – Line Reactor vs. Expected Harmonics

➤ **Advantages**

- Low cost
- Can provide moderate reduction in voltage and current harmonics
- Available in various values of percent impedance
- Provides increased input protection for VFD and its semiconductors from line transients.

➤ **Disadvantages**

- May require separate mounting or larger VFD enclosure
- May not reduce harmonic levels to below IEEE519 1992 guidelines

7.6 Using a larger DC or AC inductor

The harmonics of a voltage source AC drive can be significantly reduced by connecting a large enough inductor in its AC input or DC bus. The trend has been to reduce the size of converter while the inductor size has been also reduced, or in several cases it has been omitted totally. The effect of this can be seen from the curve forms in Figure 7.6a.

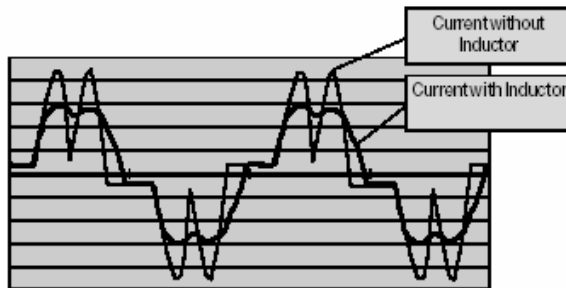


Figure 7.6a The effect of the inductor on the line current.

7.7 DC Choke

This is simply a series inductance (reactor) on the DC side of the semiconductor bridge circuit on the front end of the VFD. In many ways, the DC choke is comparable to an equivalent AC-side line reactor, although the %Total Harmonic Distortion (THD) is somewhat less. The DC choke provides a greater reduction primarily of the 5th and 7th harmonics. On higher order harmonics the

line reactor is superior, so in terms of meeting IEEE guidelines, the DC choke and line reactor are similar. If a DC choke (or line reactor) is applied on all VFDs, it is possible to meet IEEE guidelines where up to 15% to 40% of system loads are VFDs, depending on the stiffness of the line, the amount of linear loads and the value of choke inductance.

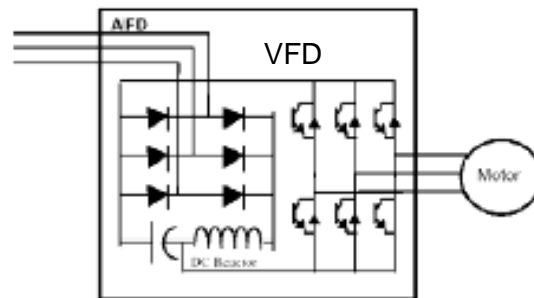
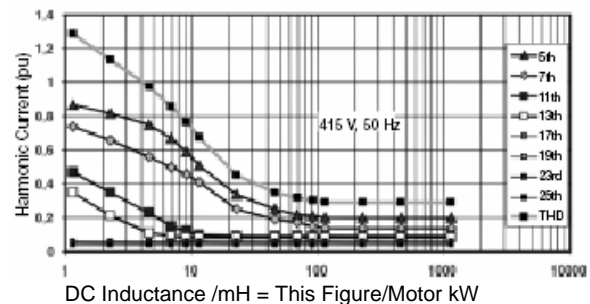


Figure 7.7a – DC Choke / VFD

The chart in Figure 6.6a shows the effect of the size of the DC inductor on the harmonics. For the first 25 harmonic components the theoretical THD minimum is 29%. That value is practically reached when the inductance is 100 mH divided by the motor kW or 1 mH for a 100 kW motor (480 V, 60 Hz). Practically sensible is about 25 mH divided by motor kW, which gives a THD of about 45%. This is 0,25 mH for a 100 kW motor.



DC Inductance / mH = This Figure/Motor kW
Figure 7.7b Harmonic current as function of DC inductance.

The voltage distortion with certain current distortion depends on the Short Circuit Ratio Rsc of the supply. The higher the ratio, the lower the voltage distortion. This can be seen in Figure 7.7b.

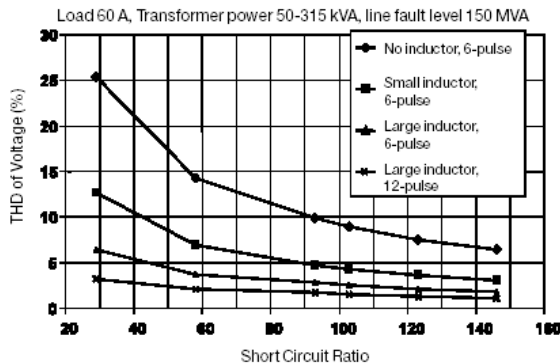


Figure 7.7c THD Voltage vs Type of AC drive and transformer size.

Figure 7.7c introduces a simple monogram for estimation of harmonic voltages. On the graph below right select first the motor kilowatt, then the transformer kVA and then move horizontally to the diagonal line where you move upwards and stop at the curve valid for your application. Then turn left to the y-axis and read the total harmonic voltage distortion.

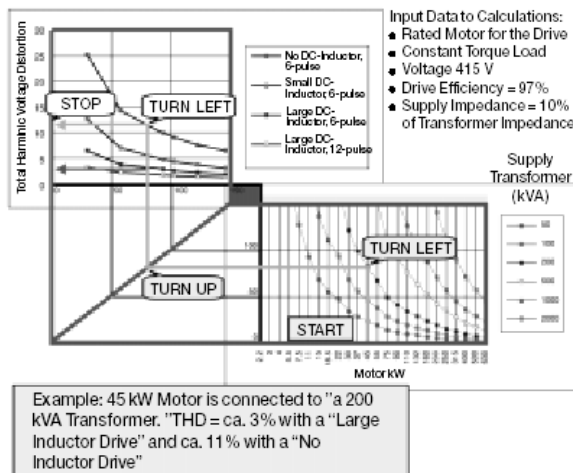


Figure 7.0 Total harmonic distortion monograms

Results from laboratory tests with drive units from different manufacturers are shown in Figure 7.7d. Drive A with large DC inductor has the lowest harmonic current distortion; drives with no inductor installed have the highest distortion.

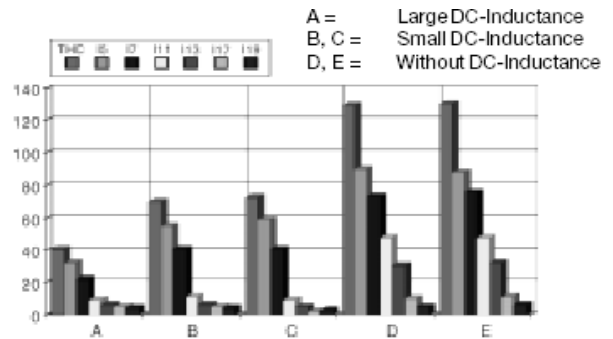


Figure 7.7d . Harmonic current with different DC-Inductances.

➤ **Advantages**

- Packaged integrally to the VFD
- Can provide moderate reduction in voltage and current harmonics
- Less voltage drop than an equivalent line reactor

➤ **Disadvantages**

- Less protection than other methods for the VFD input semiconductors
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- DC Choke Impedance is typically fixed by design (not field selectable)
- Not available as an option for many VFDs.

7.8 K-Factor and Drive Isolation Transformers

Underwriters Laboratories (UL), Canadian Standard (CSA) and transformer manufacturer established a rating method, the KFactor, for dry-type transformers to evaluate their suitability for duty in a harmonic environment. The K-factor relates the transformer capability to supply varying degrees of nonlinear load without exceeding the rated temperature rise limits of the transformer. The K-factor is based upon predicted losses as specified in the simplified method of IEEE Std C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability When Supplying Non-sinusoidal Load Current (ANSI).

The limiting factor related to overheating is again assumed to be eddy current losses in the windings. K-factor rated transformers offer no means to reduce the magnitudes of harmonic current (except that they offer line reactance – see Line Reactors). But the Kfactor method allows the engineer to choose a dry type transformer that can withstand the harmonic duty without damage or loss of performance. Standard K-factor ratings are 4, 9, 13, 20, 30, 40, and 50.

Drive Isolation Transformers are similar to K-factor transformers in that they offer line impedance similar to a Line Reactor and reduce the amount of harmonic current that is “allowed” to flow to the load but otherwise do not reduce the harmonics from the drive. Generally, they are a 1:1 ratio transformer and are used to protect other loads from the high frequencies created by the drive and are used in combinations to create a 12-Pulse Distribution System.

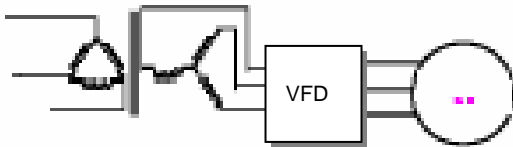


Figure 7.8a – Drive Isolation Transformer

➤ **Advantages**

- Can provide moderate reduction in voltage and current harmonics by adding source reactance.
- Can purchase various values of percent impedance according to needs
- Provides increased input protection for VFD and its semiconductors from line transients
- Can be used in combinations with line reactors and transformers for harmonic cancellation.

➤ **Disadvantages**

- K-factor transformers by themselves are a method for “living with” harmonics but will not significantly reduce the harmonics over the less expensive reactor solution.
- Must be sized (fully rated) to match each drive or group of drives.
- Cannot typically take advantage of diversity of loads.
- May not reduce harmonic levels to below IEEE519 1992 guidelines

7.9 Using Harmonic Mitigating Transformers or Multi- Pulse Distribution

This is similar to a 12-pulse converter, on a macro scale. If two VFDs of equal HP and load are phase shifted by feeding one VFD from a delta/wye transformer, and feeding the second through a delta/delta transformer or a line reactor of equivalent impedance, performance similar to 12-pulse may be achieved. The cancellation will degrade as the loads vary from VFD to VFD, although as the load on a single VFD decreases, the individual distortion contribution percentage decreases, resulting in less of a need for cancellation. It is possible for a facility with a large number of VFDs to feed two halves of the distribution from phase shifted transformers, yielding a large reduction in harmonic levels for minimal cost, and allowing a higher percentage of VFD loads under IEEE Std 519-1992 guidelines.

Multiple transformers can be used to develop different phase shifts between sources of harmonic currents. For example, two transformers with a 60 Hz phase shift of 30 degrees between them will result in cancellation of the 5th , 7th , 17th , and 19th, etc. harmonics and will resemble 12 pulse drive system. Four transformers shifted by 15 degrees with respect to each other will result in a 24-pulse distribution and will significantly minimize the resulting harmonics upstream of the common bus.

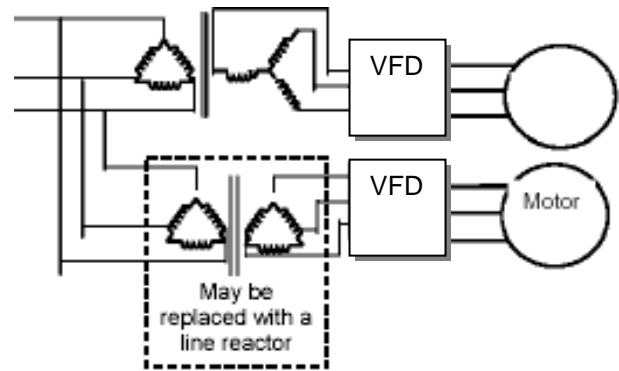


Figure 7.9a – 12 Pulse Distributions / VFD

➤ **Advantages**

- Cost may either be low or high depending on implementation
- Provides substantial reduction (50-80%) in voltage and current harmonics
- Provides increased input protection for VFD and its semiconductors from line transients

➤ **Disadvantages**

- Cost may be low or high depending on implementation
- Impedance matching of phase shifted sources is critical to performance
- Maximum cancellation occurs only if drive loading is balanced
- Transformers will require separate mounting
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines

7.10 Using Tuned single arm passive filter

Filtering is a method to reduce harmonics in an industrial plant when the harmonic distortion has been gradually increased or as a total solution in a new plant. There are two basic methods: passive and active filters.

The principle of a tuned arm passive filter is shown in Figure 7.10a. A tuned arm passive filter should be applied at the single lowest harmonic component where there is significant harmonic generation in the system. For systems that mostly supply an industrial load this would probably be the fifth harmonic. Above the tuned frequency the harmonics are absorbed but below that frequency they may be amplified.

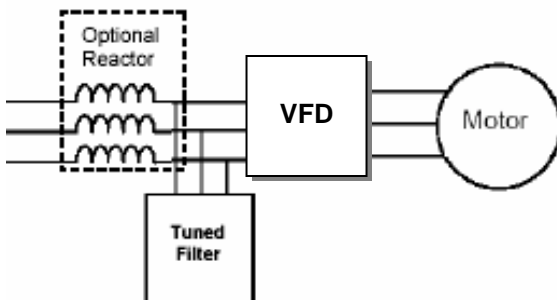


Figure 7.10a – Tuned Filter

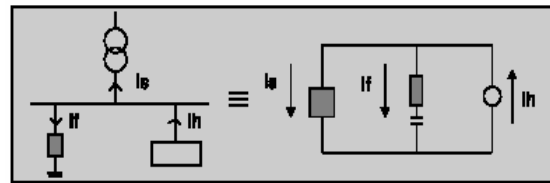


Figure 7.10b Tuned single arm passive filter.

• **Detuned - Single tuning frequency :**

- Above tuned frequency harmonics absorbed
- Below tuned frequency harmonics may be amplified
- Harmonic reduction limited by possible over compensation at the supply frequency and network itself

This kind of filter consists of an inductor in series with a capacitor bank and the best location for the passive filter is close to the harmonic generating loads. This solution is not normally used for new installations.

7.11 Using Tuned multiple arm passive filter:

The principle of this filter is shown in Figure 7.11a. This filter has several arms tuned to two or more of the harmonic components which should be the lowest significant harmonic frequencies in the system. The multiple filters has better harmonic absorption than the one arm system.

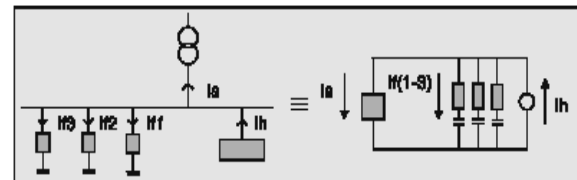


Figure 7.11a - Tuned multiple arm passive filter.

- Capacitive below tuned frequency/Inductive above
- Better harmonic absorption
- Design consideration to amplification harmonics by filter
- Limited by KVAr and network

Many times, if power factor correction is required on a power system with harmonic sources, a tuned harmonic filter will be applied in lieu of capacitors to supply the

reactive power requirements while providing a predictable resonant frequency.

➤ **Advantages**

- Allow a higher percentage of VFD system load than line reactors and chokes
- Provides power factor correction
- A single filter can compensate for multiple drives.

➤ **Disadvantages**

- Higher cost
- Separate mounting and protective device (breaker/fuse) required
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- Care is needed in application to ensure that the filter will not become overloaded
- Care is needed in application to ensure that overcompensation will not raise the voltage significantly
- Could result in leading power factors at during lightly loaded conditions

8.0 Harmonic improvement in a complete distribution network.

We utilize a wide range of techniques and tools to find, study, and correct power quality problems. Developed through years of experience with utilities and customers on power quality issues.

First off, we talk with you about your facility and the problems you are having. This helps us to determine the current situation, the operating environment of the facility and equipment, and the exact nature of the problem. We've compiled numerous case studies over the years of power quality problems, so we may be able to use them to determine what is going on before proceeding further.

Monitoring and field measurements are a key element in the problem-solving process. In addition to ensuring proper identification of a power system problem and accurate assessment of its causes, we pay particular attention to how to fix or prevent it.

Our goal is to prescribe a solution that is effective, cost-efficient, and won't cause problems for either you or the utility. We look at a wide range of corrective measures, including :

- Harmonic Filter
- Capacitors
- Surge arrestors or protectors

We feel it is important to keep you involved throughout the entire diagnostic and solution process.

Gentec the Name to remember when PQ Corrections is needed

Power quality problems can affect your productivity and your bottom line. We have the experience, know- how, and technology to identify, solve, and even prevent problems.

8.1 Using Neutral Blocking Filter

A neutral blocking filter is a capacitor and reactor combination that that is connected in series with the neutral conductor. These components are "parallel resonant" at the 3rd harmonic allowing 60 Hz (normal load) current to flow but are an extremely high impedance for the 3rd harmonic current and do not allow the load to "source" current at that frequency.

Applying this type of filter to a distribution transformer blocks all downstream loads from generating 3rd harmonics. This has the added benefit of reducing the load current (rms) from all loads and can significantly reduce the losses in the transformer and conductors between the transformer and the load.

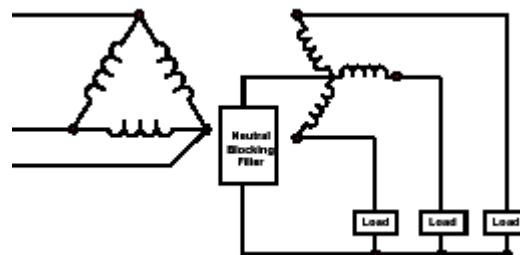


Figure 8.1 – Neutral Blocking Filter

➤ **Advantages**

- Reduces neutral currents by more than 80% (by preventing 3rd harmonic current flow)
- Decreases rms phase current by 10-30%
- Releases un-useable capacity by as much as 30%
- Removes 3rd harmonic current from all the system neutrals, from the transformer out to the furthest outlet
- Best potential for energy savings

➤ **Disadvantages**

- High cost
- Sized for transformer neutral maximum expected load
- May increase voltage distortion at load terminal.

8.2 Oversized Neutral, K-rated Transformers and/or Transformer De-rating

Understanding that magnitude of the current in the neutral circuit can approach 175% of the current in the phases when significant 3rd order harmonics are present, several methods have been developed to “live with” the increased current without spending a significant amount of money. These methods involve either increasing the harmonic capacity of the power system components or de-rating the components to accommodate the harmonic currents. One method of de-rating the power system components is to double the size of the neutral conductor. This involves increasing the neutral conductor size to twice the size of the phase conductor in any circuits where a “shared neutral” is used. This includes panelboards and shared neutral circuits such as are found in cubicle subcircuits in offices buildings, for example. Today, for many installations every circuit includes a phase conductor and its own neutral conductor.

Therefore, the only truly “shared” neutral is in the panelboard and on the transformer. However, for existing facilities, this is definitely not the case. K-rated transformers are designed to “live with” excessive harmonic currents while maintaining typical values of impedance as described earlier in

this paper (i.e., these are not simply oversized transformers). Typically, the windings and neutral have a significantly higher rating compared to a standard transformer and the standard connection is delta / wye. The delta winding is said to “trap” the triple n harmonics (3rd’s and multiples of the 3rd) but both sets of windings must be rated to accommodate the harmonic currents. For systems supplying primarily switch-mode power supply loads, a K13 or K20 may be required in order to utilize the entire rated capacity (kVA).

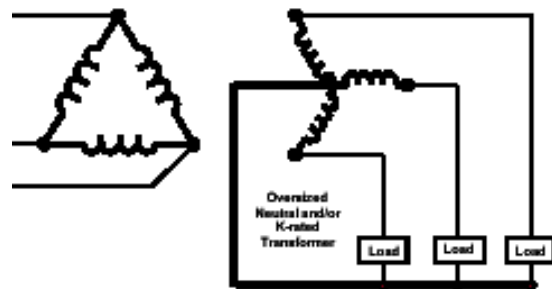


Figure 8.2a – Oversized Neutral and K-Rated Transformer

Finally, if a transformer is supplying primarily nonlinear loads and the transformer is not a K-rated transformer or otherwise transformers designed to handle harmonics, the transformer should be de-rated according to the IEEE Emerald Book recommendation in Figure 8.2b.

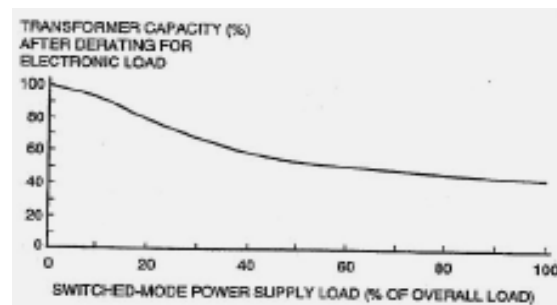


Figure 8.2b – IEEE Std 1100-1999 (Emerald Book)

Transformer De-rating Curve for Supplying Switch-Mode Power Supplies

➤ **Advantages**

- Generally, these are the least expensive methods of dealing with harmonic currents on the power system assuming that the system and other loads can deal with the excessive current and/or voltage distortion. Since most transformers are not typically loaded to their kVA rating (typical transformer loading is in the range of 30-40%), de-rating is often the most reasonable and least expensive solution.

➤ **Disadvantages**

- All of these solutions simply “live with” the excessive harmonic currents on the power system. They do not inherently reduce the current or voltage distortion.

8.3 Using Zig-zag Transformers (Zero-Sequence Traps)

The third harmonics generated by single-phase nonlinear loads flow back throughout the shared neutral. If the transformer is not designed to “handle” the excessive harmonic currents or if the upstream neutral circuit is not oversized, the harmonics must be addressed prior to the transformer. A zig-zag transformer either externally applied (also called a “zero-sequence trap”) to an existing delta-wye transformer or built into the transformer itself (the winding configuration would then be delta zig-zag, typically), provides very low impedance for 3rd harmonic (and odd multiples of the 3rd) currents.

The application of a zig-zag transformer or a delta/zig-zag distribution transformer simply provides an alternate path for the 3rd harmonic currents to flow and do not allow the current to flow back through the main step down transformer. This reduces the overall voltage distortion upstream of the transformer and/or for other parallel loads, in some cases, downstream. An optional line reactor is sometimes applied to reduce the current division between the original transformer and the new zig-zag transformer and to force most of the 3rd harmonic current through the zig-zag.

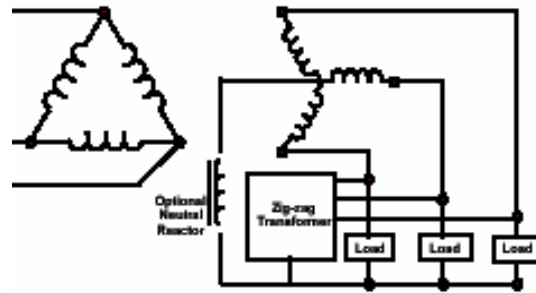


Figure 8.7 – Zig-zag Transformer

➤ **Advantages**

- May be retrofitted to existing systems or may be specified on new construction where significant single-phase harmonic currents are expected.
- May or may not increase system cost significantly depending upon the application and design.

➤ **Disadvantages**

- May or may not increase system cost significantly depending upon the application and design.
- Allows harmonics to flow but simply provides a low impedance path back to source.
- May increase available fault current by reducing the zero sequence impedance.
- May increase harmonics by reducing the source impedance from the load standpoint.

8.4 Background – Tuning

Figure 8.4b shows a typical frequency scan for a 4.1th, 4.8th, and 5th harmonic filter when placed on a system as shown in Figure 8.4b. The frequency scan shows the apparent impedance as a function of frequency as seen by an injected current at the location shown in Figure 8.4a. This injected current is usually termed a harmonic current source and usually consist of non-linear loads, such as variable speed drives, switch mode power supplies, and welders. The scan shows how the tuning point effect the apparent impedance, mainly in the area of tuning, near the 5th harmonic. A blow up of this tuning area is shown in Figure 8.4c

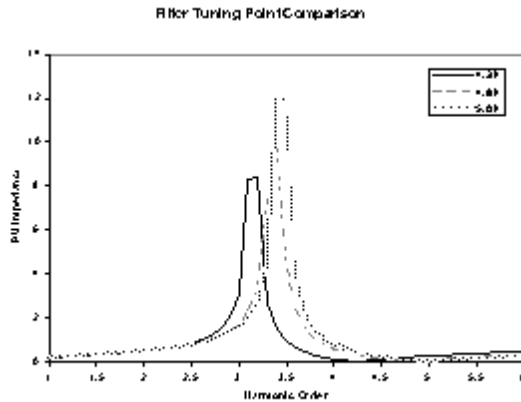


Figure 8.4b - Filter Tuning Point Comparison

The impedance scan is useful since it gives an indication of the filter characteristics and how it interacts with the system that it is being applied on. For example, the filter tuning point can be determined by looking at the minimum impedance, or "notch". In addition, the anti-resonant point, the peak just below the tuning point, can also be determined. The anti-resonant point always exists below the tuned frequency of a filter, and significant harmonics at this frequency should be avoided. When applying detuned filters below the 4.1th, careful consideration should be given to possible resonant concerns at the 3rd harmonic.

To put reality into the scans, one may say that one per unit of current injected into one per unit impedance produces one per unit voltage. In looking at Figure 8.4c, one per unit current injected into the system at the fifth harmonic will produce those voltage levels shown on the ordinate of Figure 3. That is the 4.1th will produce a 5th harmonic voltage of 0.275 per unit. The 4.8th will produce a 5th harmonic voltage of 0.072 per unit and the 5th filter a voltage of 0.006 per unit. With respect to filtering, the 5th harmonic filter perform the best of the three filters, since the lowest harmonic voltage is produced for a one per unit injection.

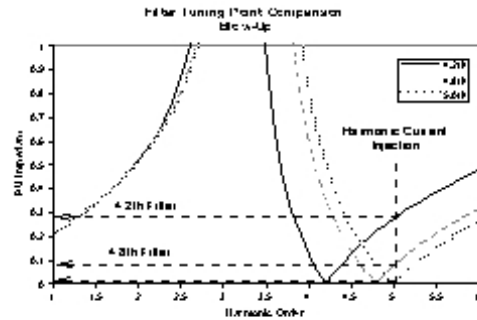


Figure 8.4c - Close up of tuning point

8.5 Using Broadband Blocking Filters

These filters are similar to Tuned Filters but have some major design differences. As Tuned Filters are connected in parallel to the harmonic loads, Broadband Filters are connected in series with the VFD and carry the full VFD current. This difference provides added protection for the input power section of the VFD. Broadband Filters require no tuning, improve power factor for the system and minimize all harmonic frequencies, including the 3rd harmonic. Additionally, they avoid system resonance and are not overloaded by harmonics from other loads.

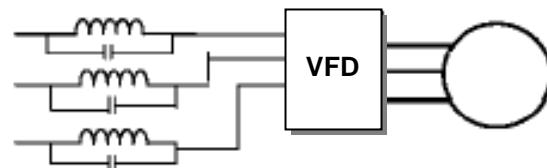


Figure 8.5a – Broadband Drive Filter

➤ Advantages

- Allows a higher percentage of VFD system load than line reactors and chokes
- Provides increased input protection for VFD and its semiconductors from line transients
- Provides added protection for VFD input power section
- Provides system power factor correction
- Typical blocking filters simulate 12/18 pulse drive harmonics

➤ **Disadvantages**

- High cost
- Separate mounting required
- Requires one filter per drive
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- Could result in leading power factors during lightly loaded conditions

8.6 Harmonic Filter Bank Tuning - Tuned & De-Tuned Banks

When designing or applying a harmonic filter, the question that comes to the mind of many engineers is; What harmonic or frequency should the harmonic filter bank be tuned too? i.e., 3.7 (de-tuned), 4.8 (partially de-tuned) or 5.0 (tuned). To answer this question, the engineer should know why the filters are being installed in the first place. Harmonic filters are generally installed to achieve one of the following objectives:

- a. Capacitors are required to improve power factor, and possible system interaction may occur with the installation of a plain capacitor bank.
- b. Permissible distortion limits of the local utility or IEEE-519 are exceeded, and filters are required to reduce them.
- c. A combination of 1 and 2 above, whereby capacitors are required to improve power factor and with the addition of the capacitors, permissible distortion limits are exceeded.

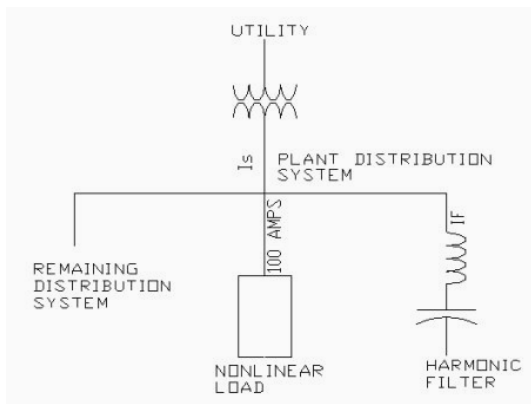


Figure 8.6a - Typical Industrial System

This technical article discusses the proper type of filter for each of the above applications and provides design and performance issues related to tuned, de-tuned and partially de-tuned harmonic filter banks. Consult Gentec for other bulletins that may assist you in the selection and application of harmonic filter banks and capacitor banks.

8.7 Using Active filter

A passive tuned filter introduces new resonances that can cause additional harmonic problems. New power electronics technologies are resulting in products that can control harmonic distortion with active control. These active filter, see Figure 8.7a, provide compensation for harmonic components on the utility system based on existing harmonic generation at any given moment in time.

This method uses sophisticated electronics and power section IGBTs to inject equal and opposite harmonics onto the power system to cancel those generated by other loads. These filters monitor the non-linear currents demanded from non-linear loads (such as VFDs) and electronically generate currents that match and cancel the load harmonic currents. Active Filters are inherently non-resonating and are easily connected in parallel with system loads. Active harmonic filters can be used to compensate for harmonics, harmonics and power factor or simply for power factor. They can also be used with existing power factor correction capacitors without concern for harmonic resonance.

Parallel (the more common type) active harmonic filters compensate for harmonic load currents. Parallel (shunt) active filters compensate for voltage distortion caused by the load by canceling harmonic load currents. Series active harmonic filters compensate for source harmonics (voltage) but do not compensate for harmonic load currents. Series filters are generally used to protect the load from damaging source harmonics whereas the shunt filters are designed to protect the system from the load

harmonic. The shunt active filter will compensate for harmonics and power factor up to its maximum capability and it cannot be overloaded.

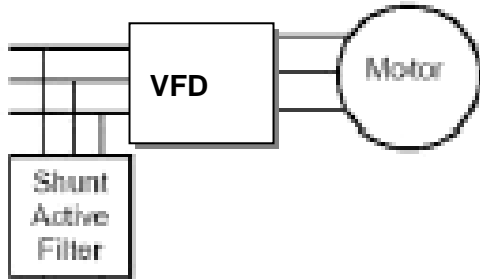


Figure 8.7 a – Shunt Active Filter

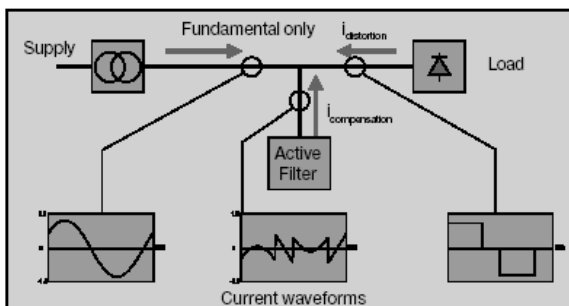


Figure 8.7b External active filter principle diagram.

The active filter compensates the harmonics generated by nonlinear loads by generating the same harmonic components in opposite phase as shown in Figure 8.7c. External active filters are most suited to multiple small drives. They are relatively expensive compared to other methods.

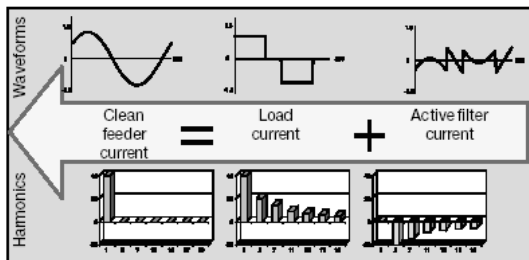


Figure 8.7c External active filter waveforms and harmonics.

➤ **Advantages**

- Guarantees compliance with IEEE Std 519- 1992 if sized correctly
- Shunt unit cannot be overloaded even as future harmonic loads are added

- Harmonic cancellation from the 2nd to 50th Harmonic
- Shunt connected unit provides easy installation with no major system rework
- Provides reactive (var) currents improving Systems power factor
- Can be designed into an MCC to compensate for several VFDs
- Typically more expensive than other methods due to the high performance control and power sections
- Series unit must be sized for total load

➤ **Disadvantages**

- High cost
- Separate mounting required
- Requires one filter per drive
- May not reduce harmonic levels to below IEEE Std 519-1992 guidelines
- Could result in leading power factors during lightly loaded conditions

9.0 Filter Performance

From the above discussion, it is apparent that tuning has a definite effect on filter performance and system interaction. The question of whether to tune, de-tune or partially de-tune is a question of economics, objective of filtering, and negative system interaction. A tuned filter cost more than a partially de-tuned filter, and likewise a partially de-tuned filter cost more than a de-tuned filter. The reason for the cost difference, is the duty requirements for both the capacitors and the reactors.

For example, the filter currents for various tuning points for the typical system in Figure 9.0a are illustrated in Table 1. The Table 1 is based on 100 amps of 5th harmonic current injected from the non linear load. This current may flow back to the utility or into the harmonic filter, and is dependent upon the filter impedance and system impedance at the 5th harmonic. Table 1 shows that the 5th harmonic filter will absorb most of the harmonic current and that very little will be absorbed by the utility. As a result, the fifth harmonic filter would require a 5th harmonic current

rating of 99 Amps. The 4.8th harmonic filter absorbs less, and would require a 5th harmonic current rating of 70 Amps. The 4.1th harmonic filter absorbs very little harmonic current (20 Amps), while the utility and the remaining system absorbs the remaining 80 Amps. The conclusion here is simple, tuning the filter closer to the fifth harmonics requires higher reactor current ratings, (and also capacitor voltage ratings) which result in higher filter bank cost.

Table 1 - Filter Performance

| Filter Type | Filter Current (amps) | Utility System (amps) |
|-------------|-----------------------|-----------------------|
| 5th | 99 | 1 |
| 4.8th | 70 | 30 |
| 4.1nd | 20 | 80 |

9.1 De-tuned Filters (Tuning between 4.1 and 4.4)

If harmonic filters are being considered only for the purpose of power factor correction, then a de-tuned filter bank is the best choice. This filter will do little for removing any harmonic distortion present on the system but will allow the installation of a large capacitor bank without any adverse system interactions. De-tuned filter banks are less costly an are more reliable than partially de-tuned and tuned filter banks. The anti-resonant frequency should be considered to assure that it does not fall near the 3rd harmonic.

9.2 Partially Tuned Filter (Tuning between 4.1 and 4.8)

In some situations, a filter (or capacitor bank) is required to improve power factor, and at the same time distortion limits are exceeded. In this situation, a partially tuned filter bank is usually the best choice. A partially tuned bank offers less risk and is typically less costly than a tuned filter bank.

97.3 Tuned Filters (Tuning between 4.8 and 5.0)

If harmonic filters are being considered only for the purpose of reducing the harmonic distortion to acceptable limits, then a tuned filter bank should be considered. A tuned filter bank will require the least amount of kvar to bring the distortion down within limits, but will require the highest level of engineering design. It has the highest level of risk, since it will draw most of the harmonics present on the industrial system and local utility system. Harmonic load growth should be considered, along with ambient voltage distortion level. The application of this type of filter should include a detailed harmonic analysis by the manufacturer.

Other Filter Types

Fifth harmonic filters have been the main topic of discussion. Other types of filters are some times required, i.e., 5th, 7th, 11th filter banks. Or 5th, 7th, 11th and 13th high pass. These filters are designed with optimization and with specific current distortion limits in mind. They are more costly then simple tuned filter banks but are much more effective in reducing the system distortion. They are generally applied to systems with large amounts of non-linear load.

9.4 Shunt Active Filter

Conclusion

The choice of tuning frequency is based on the objective of the harmonic filter and economics. The following guidelines may assist the engineer in determining the proper type (tuning frequency) of filter.

10. SPECIAL CONSIDERATIONS FOR APPLYING CAPACITORS IN A HARMONIC ENVIRONMENT

Capacitors are generally applied to a power system for one of three reasons:

- Improve power factor
- Increase system capacity especially in transformers or cables (by reducing total kVA)
- Improve kW efficiency – i.e. reduce total load current resulting in reduction of I²R losses. When harmonics exist on a system with capacitors, consider the following:
 - Parallel and series resonance frequencies will exist
 - Harmonics typically appear as reactive power components – more harmonics = lower power factor

Sometimes, if you are trying to improve the power factor, the result may be harmonic resonance (a negative result). Sometimes, if you are trying to reduce the harmonics flowing in the power system, you may actually improve the power factor (a positive result).

Care must be taken to understand the complex relationship between capacitors and harmonics.

11. Harmonic Resonance Explained

Whenever a capacitor bank exists on a power system, both a parallel and series resonant point exists. Typically, series resonance results in extremely high harmonic currents and causes nuisance fuse or breaker operations or overloads. However, parallel resonance results in extremely high voltages and currents and can cause significant physical damage. Care must be taken to avoid both potentially damaging resonant conditions.

The operation of non-linear loads in a power Distribution system creates harmonic currents that flow throughout the power system. The inductive reactance of a power system increases with frequency (i.e. as the harmonic order increases). The capacitive

reactance decreases with frequency (i.e. as the harmonic order increases). At some given harmonic frequency in any system where a capacitor exists, there will be a crossover point where the inductive reactance equals the capacitive reactance. Parallel resonance is the coincidental similarity of system impedances. Every system with a capacitor has a parallel resonant point.

Parallel resonance causes problems only if a source of harmonics exists at the frequency where the impedances match. This is typically called harmonic resonance. It's extremely unlikely that these two impedances are exactly identical but near resonance can be very damaging. If, for example, the parallel resonant point was at the 5.3rd harmonic and a source of 5th harmonic current existed on the system, problems will likely exist, equipment misoperation, for example. Whereas, if the resonant point were the 5.05th, the capacitor bank may fail violently.

In short, harmonic resonance can occur if both of the following are true:

11.1 Harmonic producing loads are operating on the power system. Examples of these loads are:

- AC/DC Drive Systems
- Induction Heaters
- Arcing Devices
- Switch-Mode Power Supplies
- Rectifiers

11.2 At a specific location in a power system, a capacitor, or a group of capacitors, and the source impedance have the same reactance (impedance) at a frequency equal to one of the characteristic frequencies created by the loads

– i.e. the system is parallel resonant at a frequency that is equal to one of the harmonics flowing on the power system. Note that the capacitor can be in the form of a passive harmonic filter (reactor/capacitor combination).

12. What is an Obvious Sign of Parallel Harmonic Resonance?

Generally, parallel harmonic resonance is a phenomena triggered by an event where the harmonic source changes or where the source impedance or capacitor size changes (i.e. if capacitors are switched on or off in steps). When installing power factor correction capacitors, the resulting parallel resonant frequency, or harmonic order, can be estimated using the following equation:

$$h_R = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}}$$

where,

h_R is the parallel resonant harmonic (i.e. 5th, 7th, etc.)

MVA_{SC} is the source impedance at the bus of interest, in MVA

$MVAR_{CAP}$ is the three-phase rating of the capacitor bank in MVA

For example, if the source impedance at a bus is 500 MVA, a capacitor bank of 10 MVA will be resonant with that source impedance at the 7th harmonic.

$$h_R = \sqrt{\frac{500}{10}} = 7.07$$

Therefore, if any magnitude of 7th harmonic current flows on the power system at that bus, the effect could be catastrophic.

When you are taking measurements, if a resonant condition exists, one or more of the harmonic currents will be uncharacteristically high. Normally, the characteristic harmonics decrease as frequency increases (i.e. the 5th should be higher than the 7th, the 7th higher than the 11th, etc.). Harmonic resonance can be evident in the voltage measurement but it may not be as obvious or significant.

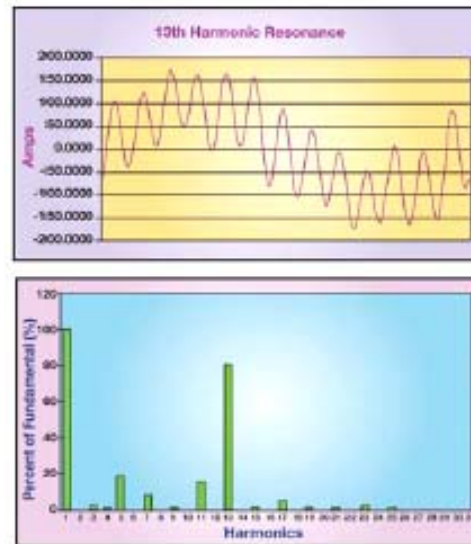


Figure 12 – Harmonic Waveform and Spectrum for 13th Harmonic Resonance

If the non-linear loads generate harmonic current at the resonance frequency, large harmonic voltages develop at the capacitor and transformer bus, and serious equipment damage may occur.

Unfortunately, harmonic resonance is said to be a “self correcting problem” – most times, capacitor fuses open, capacitor cans fail or the source transformer fails – any of which removes a component that causes the resonant condition and all of which are undesirable results. In a best-case scenario, the electrical control equipment acts erratically.

13. Avoiding Harmonic Resonance

Since capacitors are primarily added to a power system to improve the overall power factor to a desired level, the size of the capacitor is selected based upon the required kvar for compensation of the loads. Therefore, if the selected capacitor is going to cause resonance with the system, you only have two choices:

1. Apply another method of kvar compensation (harmonic filter, active filter, synchronous condenser, etc)
2. Change the size of the capacitor bank to overcompensate or under-compensate for the required kvar and live with the

ramifications. The correct choice really depends on the situation. If a harmonic filter could relieve the power factor penalty and reduce the overall system harmonics, perhaps this is your best choice. Otherwise, simply changing the size of the capacitor is typically the least expensive solution as long as the overvoltage resulting from overcompensation or the power factor penalty resulting from under compensation are acceptable.

Special considerations are also very important for switched power factor correction banks. Every step (capacitor size) must be evaluated to determine possible resonant conditions. The accompanying graph shows a six-step capacitor bank versus harmonic resonant order. This graph highlights (red lines) the orders to avoid (5th, 7th, 11th, etc.). If this same bank were designed as a harmonic filter, the parallel resonant point at any given stage would be equal to approximately 3.5th harmonic – well below the 5th harmonic current, the lowest significant harmonic on this power system.

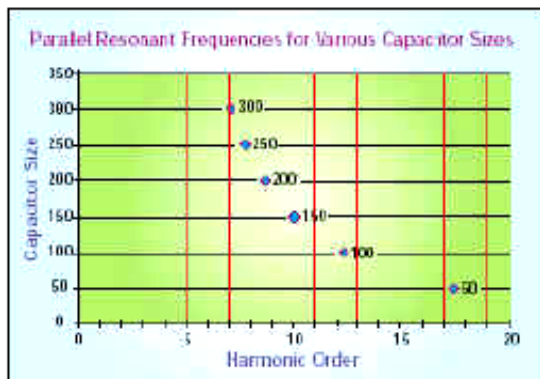


Figure 13 – Parallel Resonant Plot of 6-Step Capacitor Bank Switched in Stages of 50 kvar

14. HOW CAN REDUCING HARMONICS SAVE YOU MONEY?

Correcting a harmonics problem can save money in obvious ways if the problem resulted in physical damage to equipment or misoperation of equipment. Alleviating these issues show an immediate payback if the damage or the cost associated with the misoperation are more substantial than the cost of the solution. Other subtle but sometimes significant issues arise as a

result of harmonic currents flowing throughout the power system distorting the voltage. These issues primarily relate to the costs associated with the efficiency of power system equipment operating at frequencies other than the 50 or 60 Hz for which they were designed.

The following are some ways that harmonics can cost you money without you realizing it.

14.1 Transformers, motors, generators, cables and UPS systems are often over designed when harmonics are present and the cost associated with this over design is or can be significant. Consider the following example.

If a backup generator is sized for the kW or kVA of load and supplies power to harmonic loads, the resulting voltage distortion will be substantially higher than when the same loads are supplied by the utility source (transformer). Figure 8 shows the difference between voltage distortions when the source is the utility versus the backup generator. Note that the generator typically has at least three times the impedance of the transformer causing significantly more distortion. For this reason, generators are often oversized to “handle” the current distortion.

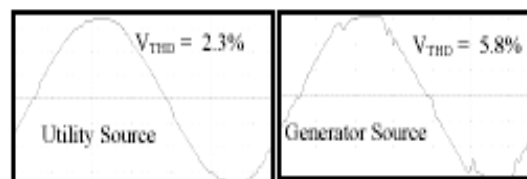


Figure 14 – Voltage Distortion on Utility Source vs. Backup Generator (Same Load)

14.2 kW losses in cables, transformer, generators and motors are significant when you consider that the root-mean-square (rms) current may be typically 10-40% higher than it would be with the current doing the “work” – the 50 or 60 Hz current. Reducing the harmonic current on downstream loads (using a blocking filter on a circuit with substantial 3rd harmonic loads, for example) can reduce system losses by 3-8%. The savings associated with this reduction in losses can typically pay for the solution in a reasonable period of time.

14.3 If the system voltage becomes distorted as a result of significant harmonic loads, and an appreciable amount of “negative sequence” voltage is present (5th harmonic, for example), motors will draw a 5th harmonic current. This current produces a reverse and pulsating torque opposing the motors preferred direction that the motor must overcome to do its required work. Constantly fighting this reverse torque makes the motor hot and very inefficient. Premature motor failures and substantial losses will result. In this case, the voltage distortion should be corrected but it may not be immediately evident that a problem even exists.

4. Low power factor as a result of harmonic currents can contribute to a power factor penalty from the utility. Depending upon the method of calculation that the utility uses, the total power factor (including harmonics) or displacement power factor (fundamental voltage and current only) can result in a significant difference in power factor on your bill. As noted earlier, significant harmonic distortion will often result in a low total power factor. Disadvantages for each solution are shown in the main body of this paper. Each solution has merit given different circumstances. Selecting the right solution requires experience with each type of technology to insure that it is the best technical and economic solution for the application.

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3. T. Key and J. Lai, “Cost and Benefit of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building,” in IEEE Transactions on Industry Applications, Vol. 32, No 5, September/October 1996.